I.B DESIGN OF THE TEM

The TEM Top to Bottom:

- Electron gun
- Condenser lens(es)
- Lens aberrations
- Objective lens and specimen stage
- Projector lenses
- Camera and viewing system
- Vacuum system
- Electrical system

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- Electrical system

I.B.4 Objective Lens and Specimen Stage

KEY CONCEPTS

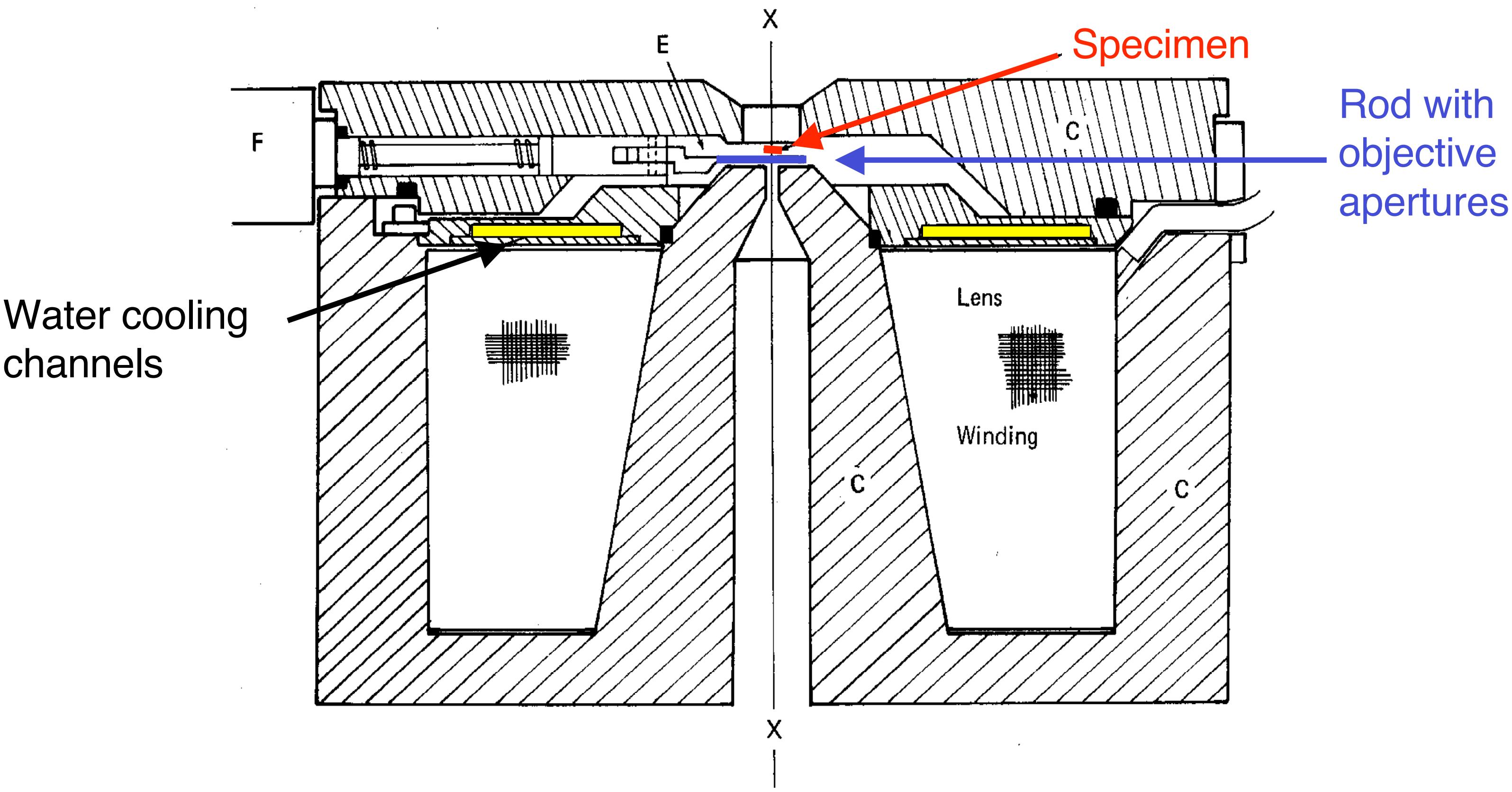
- Objective lens is most critical lens of TEM

- Performs the first stage of imaging

- Determines the instrument resolving power and contrast

I.B.4 Objective Lens and Specimen Stage

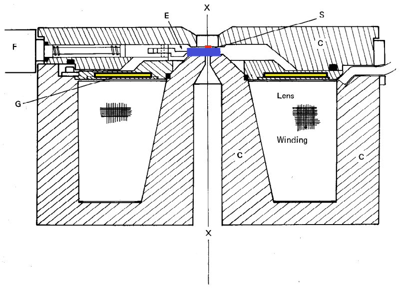
I.B.4.b Objective Lens Construction



From Agar, Fig. 2.11, p.51

I.B.4 Objective Lens and Specimen Stage

I.B.4.b Objective Lens Construction



Requirements

- **Specimen** situated **close to** objective **front focal plane**
- **Focal length** should be as **small as practical** (minimizes chromatic & spherical aberration which decrease as focal length decreases)
- Specimen has to be ***inside*** the **lens field** to obtain the necessary short focal length (specimen in a confined space)
- Need adequate clearance for insertion of specimen, aperture, and anticontaminator
- Must provide for inserting devices (stigmators) to correct for asymmetries in the lens field

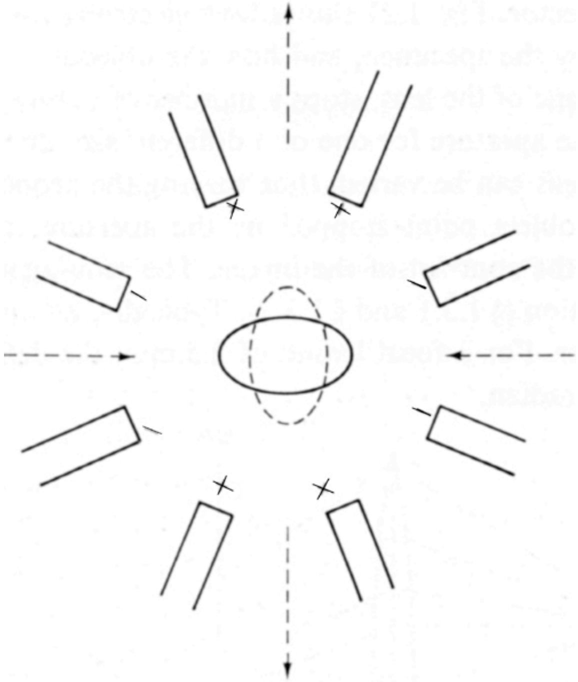
I.B.4 Objective Lens and Specimen Stage

I.B.4.c Objective Lens Asymmetry

- Impossible to manufacture lenses with perfectly rotationally symmetric magnetic fields about the optic axis
- If field is not perfectly symmetrical, the image will be **astigmatic** on as well as off the axis
- In older microscopes, **stigmators** consisted of iron pieces (**octupole**) that could be physically moved to make the field more symmetrical

Octupole: arrangement of magnets used to make the magnetic field of the objective lens symmetrical

- Modern microscopes use electrostatic fields to correct lens astigmatism



From Agar, Fig. 1.22, p.28

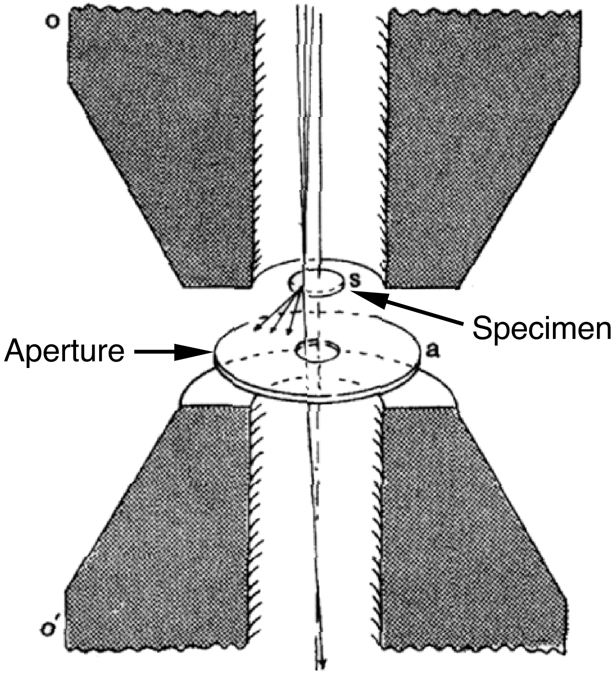
I.B.4 Objective Lens and Specimen Stage

I.B.4.e Objective Aperture

FUNCTION: Intercepts e^- which have been scattered by the specimen through **large angles**

POSITION (most common): ***Back* focal plane** of the objective lens

Lengthwise section through objective lens pole pieces.



From Wischnitzer 2nd ed., Fig. 51, p.60

- Does not restrict field of view

- Contamination effects reduced in this position since only widely scattered e^- strike the periphery of the aperture opening

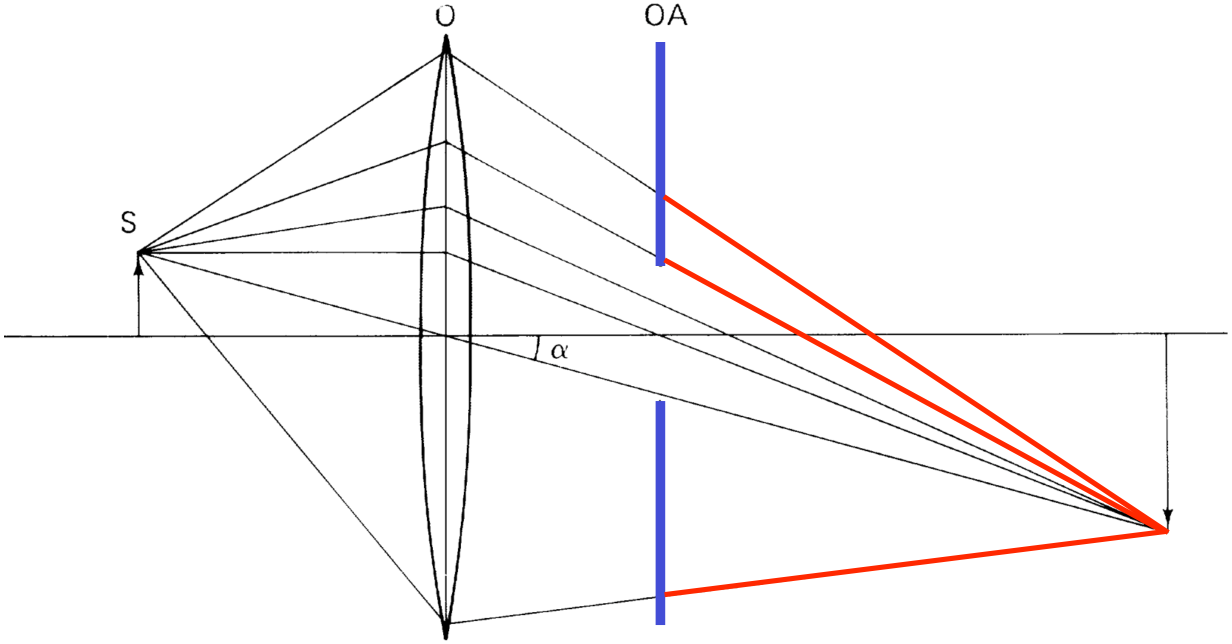
I.B.4 Objective Lens and Specimen Stage

I.B.4.e Objective Aperture

FUNCTION: Intercepts e$^-$ which have been scattered by the specimen through **large angles**

POSITION (most common): ***Back* focal plane** of the objective lens

In this position, the objective aperture screens out widely scattered electrons from being imaged



From Agar 2nd ed., Fig. 1.21, p.27

I.B.4 Objective Lens and Specimen Stage

I.B.4.e Objective Aperture

Factoids, Factoids, and even more Factoids:

- **~ 25-75μm** hole diameter

- **Smallest** apertures give **best image contrast**

- Must be **perfectly circular** and **clean** (or imaging field will be distorted)

  Contaminated aperture can act like a weak electrostatic lens causing image astigmatism

- Difficult to manufacture with good circular symmetry

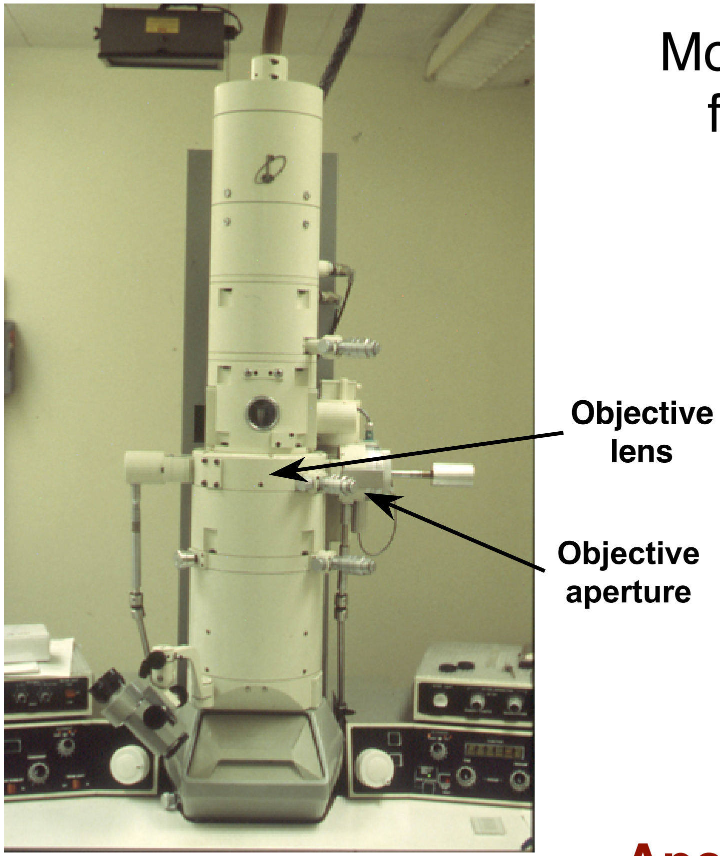
- Contamination effects more serious with smaller apertures

- Use **ultrathin, self-cleaning** metal apertures

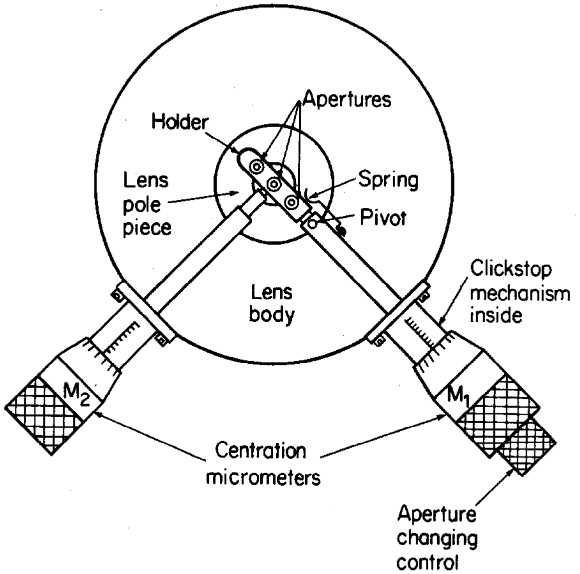
- Older TEMs: platinum or molybdenum apertures (need regular cleaning)

I.B.4 Objective Lens and Specimen Stage

I.B.4.e Objective Aperture



Most TEMs have an aperture holder with space for 3 apertures



From Meek, 1st ed., Fig. 5.2, p.95

Aperture centering (simplest method):

Image the **back focal plane** of the objective lens on the fluorescent screen (TEM in SA diffraction mode)

I.B.4 Objective Lens and Specimen Stage

I.B.4.f Specimen Stage

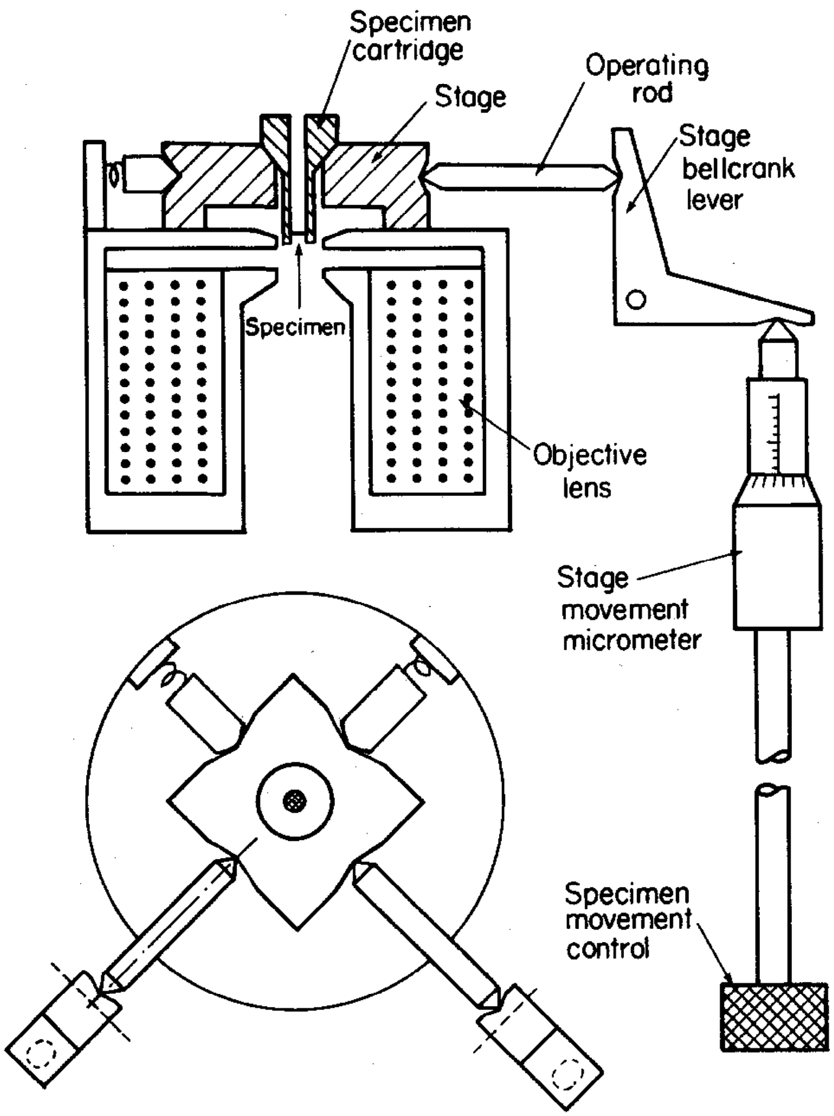
Requirements of Suitable Stage

- Allow simple and rapid specimen exchange
- Must have a specimen **airlock**
- Should sit in a plane well defined with respect to its position along the axis of the optical system
- Provide **minimum backlash** (<100 nm) - no drift
- Provide minimal vibrations, thermal motions, mechanical drift, and movements
- Make **good thermal contact** with specimen

I.B.4 Objective Lens and Specimen Stage

I.B.4.f Specimen Stage

Top Entry Stage



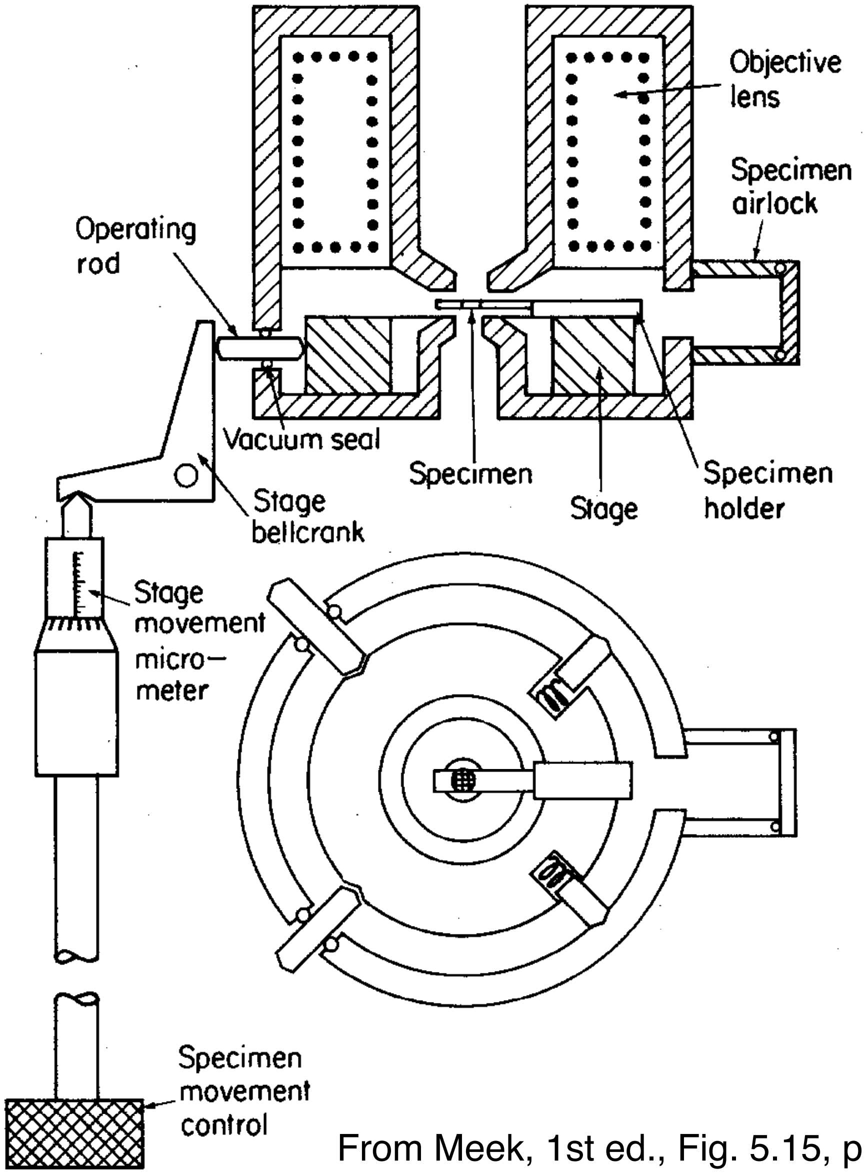
Drop-in cartridge type of objective lens, stage, and stage motion.

From Meek, 1st ed., Fig. 5.14, p.114

I.B.4 Objective Lens and Specimen Stage

I.B.4.f Specimen Stage

Side Entry Stage



The side-specimen-entry, immersion type of objective lens, stage, and stage motion

From Meek, 1st ed., Fig. 5.15, p.115

I.B.4 Objective Lens and Specimen Stage

I.B.4.g Special Stages

One for nearly every need!!!

- Tilt stage
- Multiple specimen stage
- Furnace heating stage
- Grid heater stage
- Cold stage
- Straining stage
- Gas reaction stage
- Hydration or ‘wet’ stage
- Many, many more….

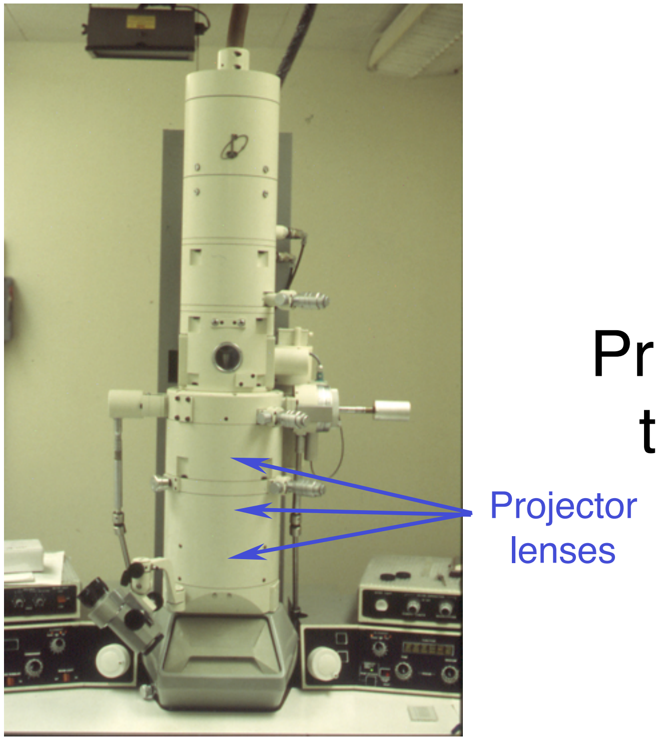
See lecture notes (p.48) for more details

End of Sec.I.B.4

I.B.5 Projector Lenses

I.B.5.a Description

Projector Lens Systems



Produce and control magnification of the final image

- Modern instruments use 3 or 4 projector lenses (diffraction, intermediate, and one or two projector lenses) to give a wide magnification range

- Each microscope has a different formula for producing a wide range of image magnifications (typically ~ 1000X up to >500,000X)

- **Object** of 1st projector lens: intermediate image produced by objective lens

- Last projector lens magnifies an area of the 2nd or 3rd intermediate image that may be several millimeters in diameter

I.B.5 Projector Lenses

I.B.5.b Distortion

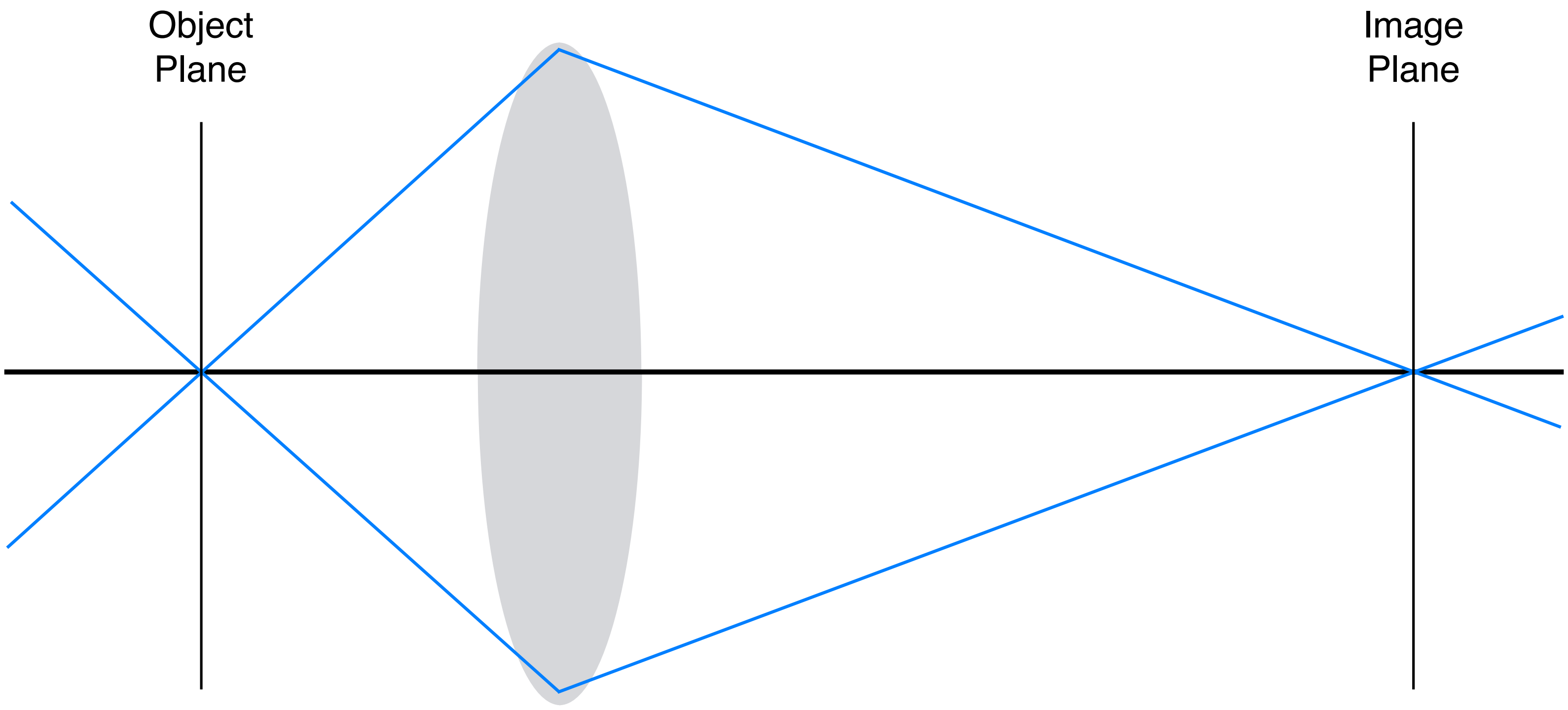
- Aberrations in the projector lenses do **not** influence **resolution** of final image but may produce some image distortion (barrel, pincushion, spiral)

See lecture notes (pp.37-39 and p.49) for details

I.B.5 Projector Lenses

I.B.5.c Depth of Field and Depth of Focus

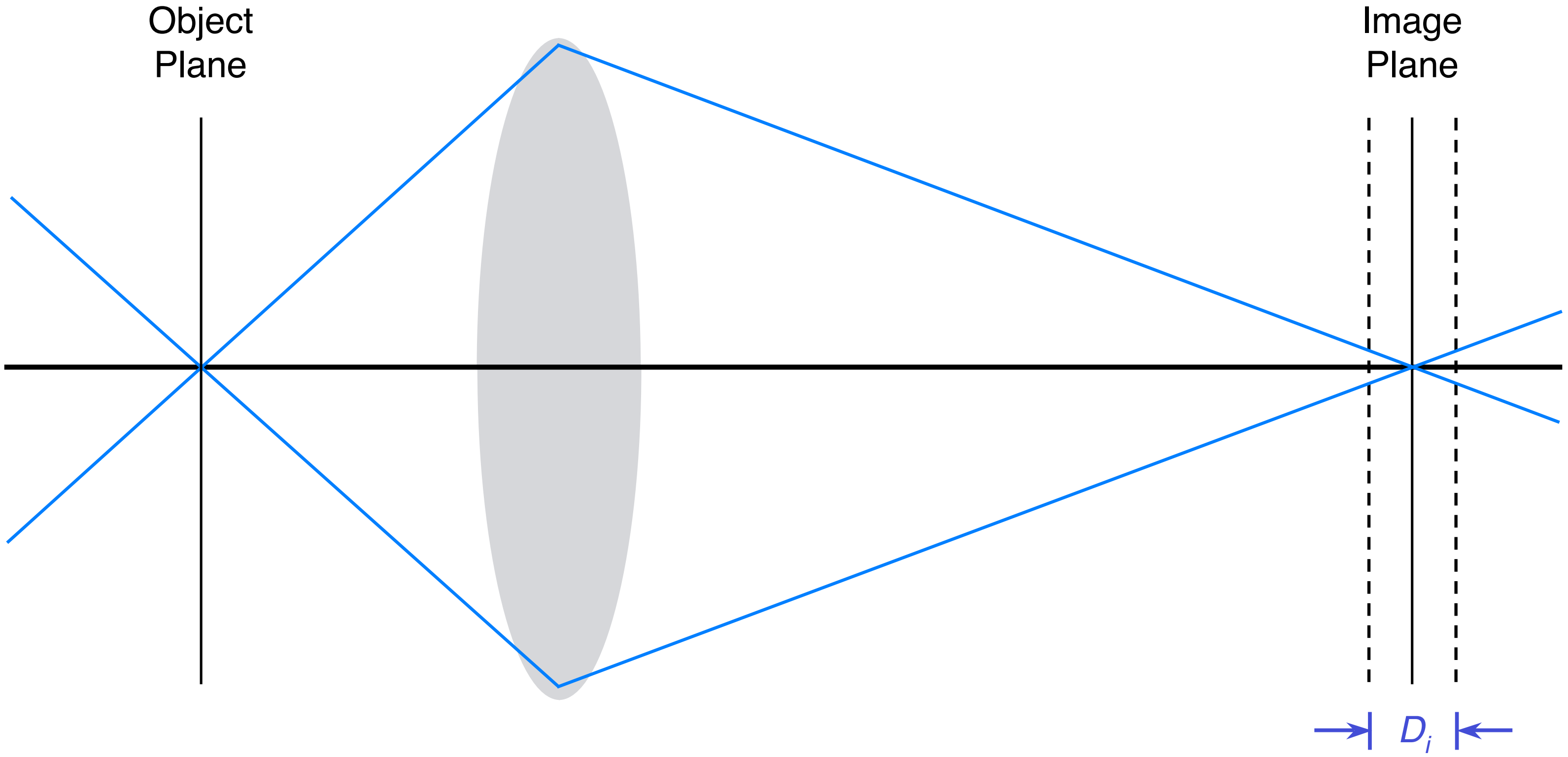
Recall: Any lens, however perfect, can only image a point object as an Airy disc, the diameter of which = lens resolving power



I.B.5 Projector Lenses

I.B.5.c Depth of Field and Depth of Focus

There is a finite distance along the axis, D_i, where the image appears equally sharp. This is distance is called **depth of focus.**



I.B.5 Projector Lenses

I.B.5.c Depth of Field and Depth of Focus

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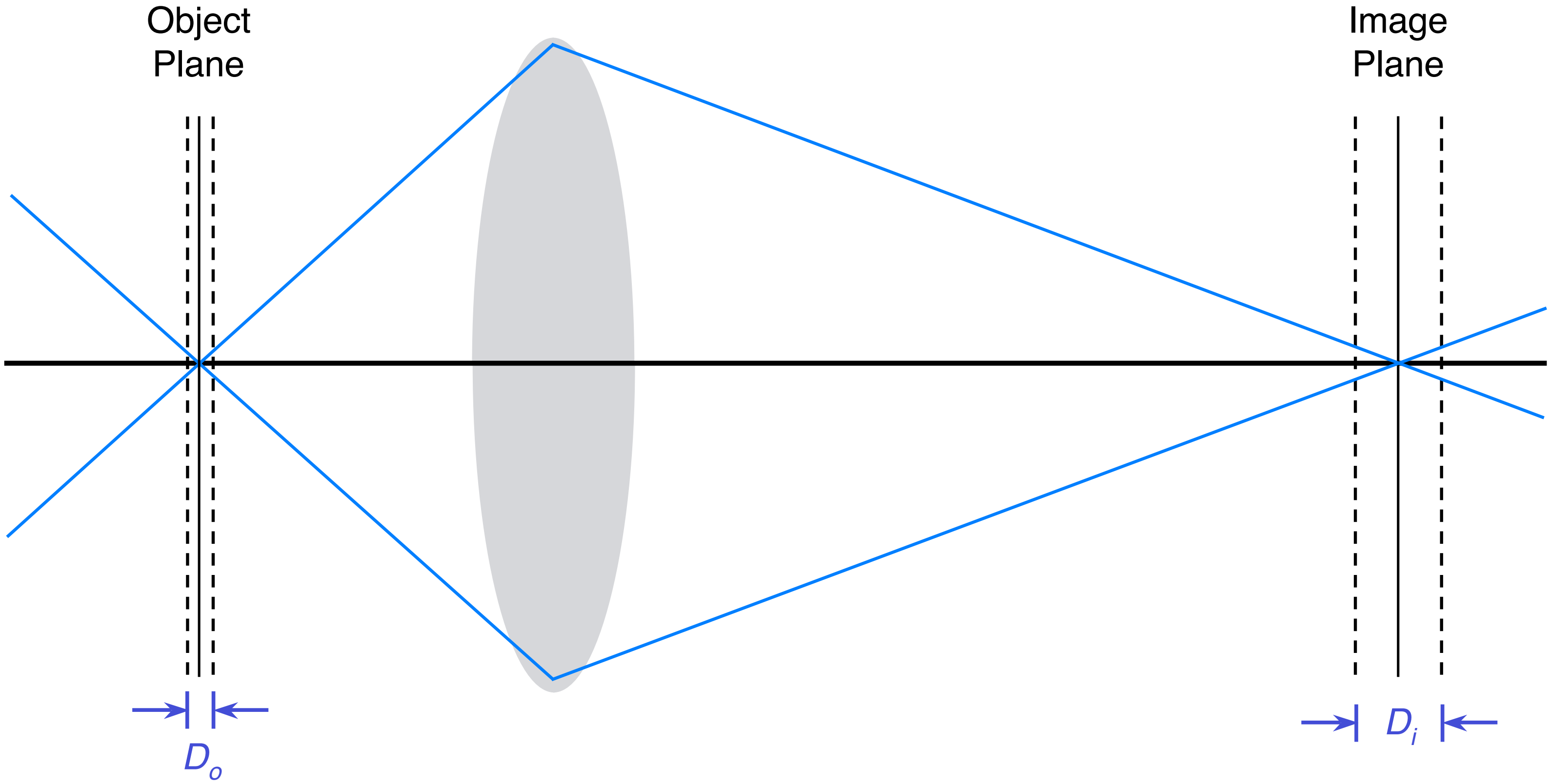
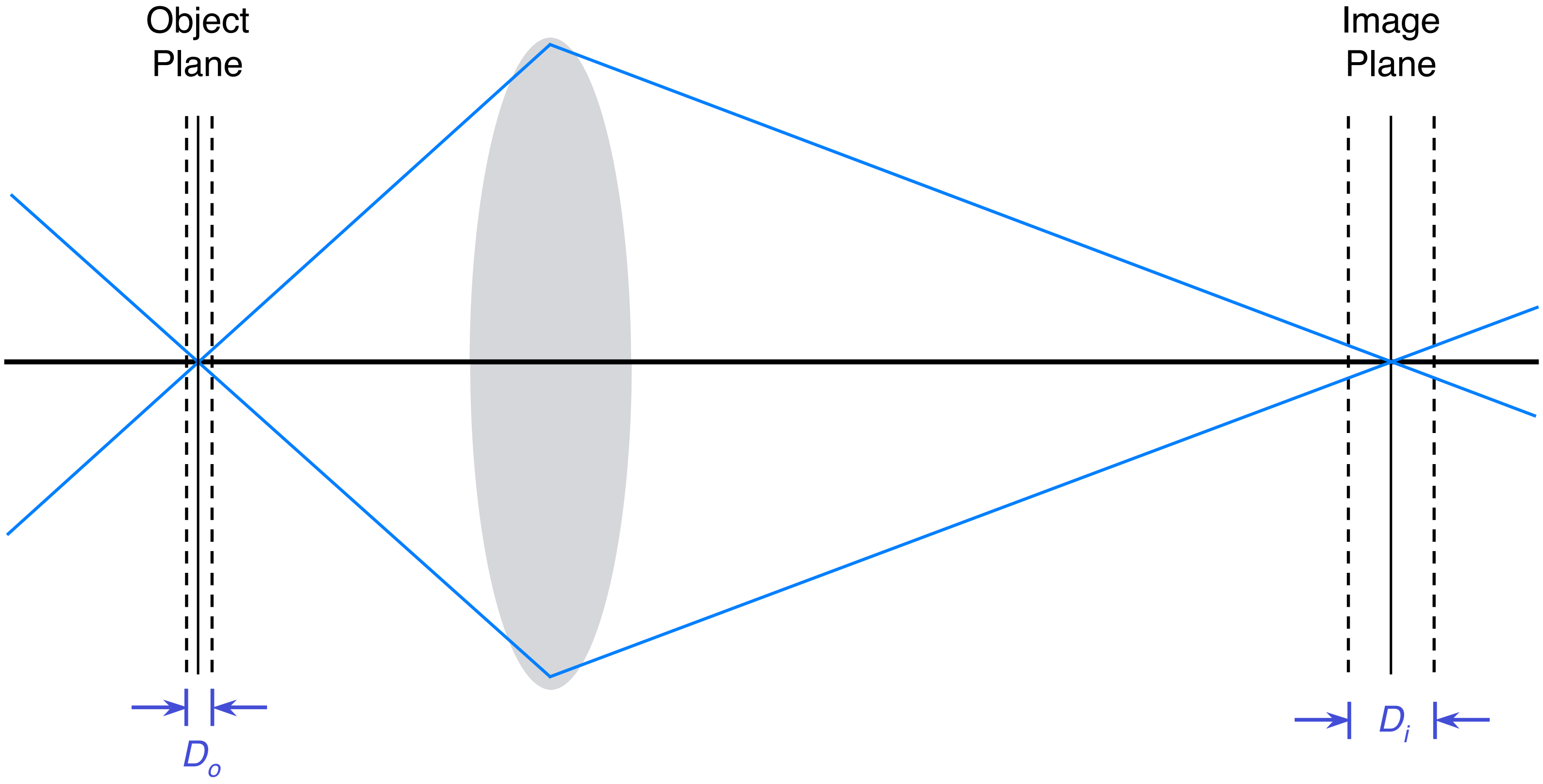


An analogous distance, D_o, along the axis on the **object side** over which the object could be moved and still give a maximally sharp image (at position of "exact" image plane). This distance is called the **depth of field.**

I.B.5 Projector Lenses

I.B.5.c Depth of Field and Depth of Focus

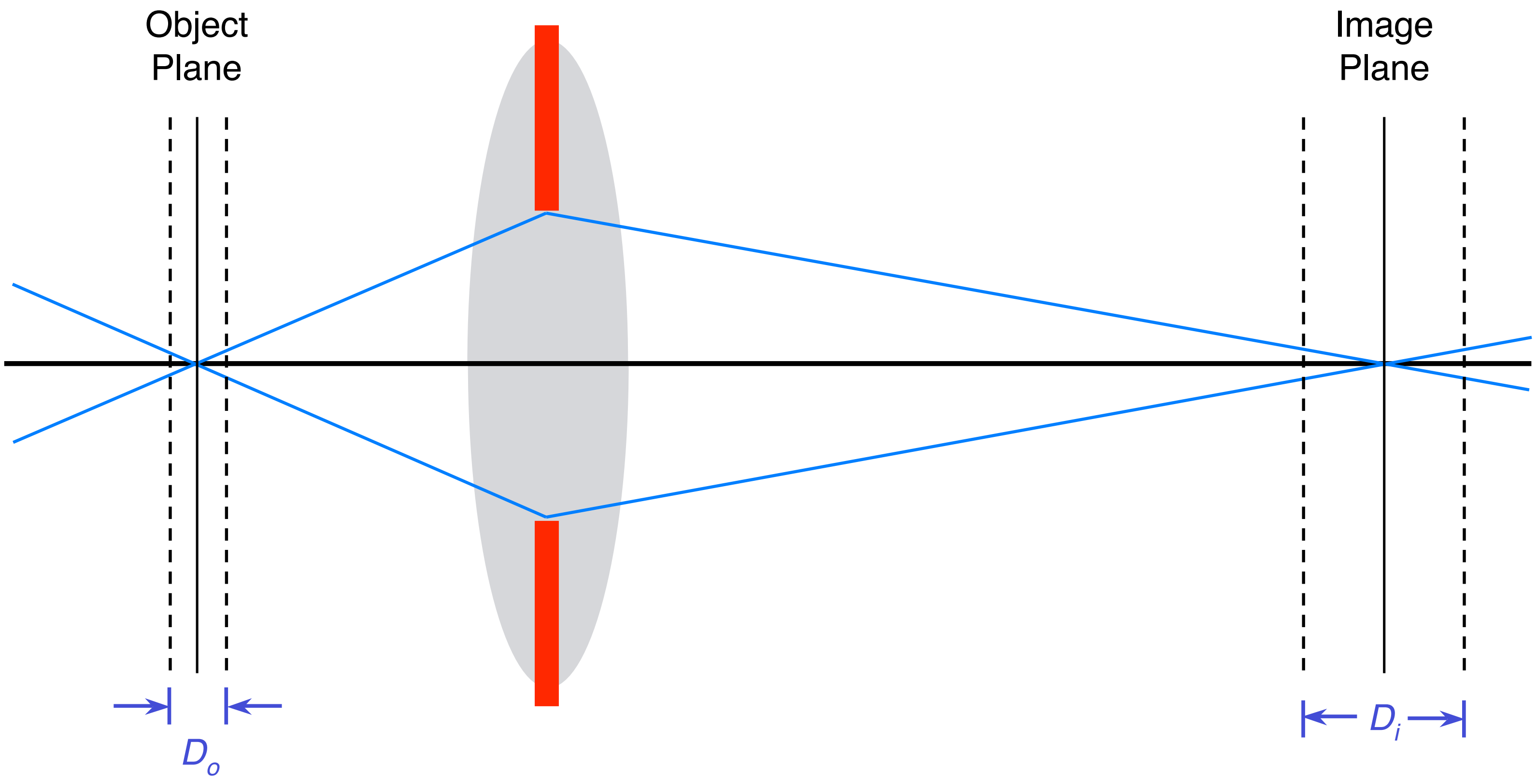
Decreasing the aperture of the lens *increases* **both** D_o and D_i.



I.B.5 Projector Lenses

I.B.5.c Depth of Field and Depth of Focus

Decreasing the aperture of the lens *increases* **both** D_o and D_i.



I.B.5 Projector Lenses

I.B.5.c Depth of Field and Depth of Focus

Depth of Field (Object/Specimen Plane)

$$D_o = \frac{2d}{\tan \alpha_o}$$

d = minimum object spacing one hopes to resolve

α_o = **objective lens** semi-angular aperture

EXAMPLE: For $d = 1.0$ nm and $\alpha_o = 5 \times 10^{-3}$ radians, $\boldsymbol{D_o = 400}$ **nm**
(thicker than most TEM specimens)

CONSEQUENCE: A thin specimen appears equally sharp through its entire thickness

I.B.5 Projector Lenses

I.B.5.c Depth of Field and Depth of Focus

Depth of Focus (Image Plane)

$$D_i = \frac{M^2 2d}{\tan \alpha_o} = D_o M^2$$

M = **total** magnification of compound magnifying system

d = minimum object spacing one hopes to resolve

α_o = **objective** lens semi-angular aperture

EXAMPLE: If $M = 50{,}000$X, $d = 1.0$ nm, and $\alpha_o = 5\text{x}10^{-3}$ radians, then

***D_i* = 1000 meters!!!**

I.B.5 Projector Lenses

I.B.5.c Depth of Field and Depth of Focus

Consequences (Key Concepts):

- Fluorescent screen, photographic plate or film can be placed **ANYWHERE** on the optic axis beneath the projector lens and the final image **will be in equally sharp focus** (though magnification **WILL** differ)

- Large depth of field/focus does **NOT** eliminate the requirement for **VERY CAREFUL FOCUSING** of the image (by adjusting the objective lens strength)

Ugh…..just when you thought something might be easy!

I.B.5 Projector Lenses

I.B.5.c Depth of Field and Depth of Focus

Factoids:

- **LM:** depth of field and depth of focus are roughly the same magnitude

- **TEM:** depth of **focus** is many times greater than the depth of field (by the factor = M^2)

End of Sec.I.B.5

I.B DESIGN OF THE TEM

I.B.6 Camera and Viewing System

I.B.6.a Viewing the Image

- Electron optical image is projected onto a fluorescent screen

- Fluorescent screen: surface coated with a layer of activated zinc sulfide crystals

- Kinetic energy of electrons in the image is transformed into light energy through fluorescence

- Resolution of image on **screen** determined by size of these crystals (~50-75 μm)

I.B.6 Camera and Viewing System

I.B.6.b Photographing the Image

- Photographic recording done at magnification sufficient to maintain resolution in electron image

- Resolution of photographic emulsions generally ~ 4-5 times better than the fluorescent screen

- **Exposure time** may be determined from a reading taken by a photo-cell looking at the fluorescent screen or by reading the current on the screen itself

- Most common types of photographic materials are 3x4" sheets of film, 35mm film, and 70mm roll film

I.B.6 Camera and Viewing System

I.B.6.c Photographic Emulsion

- **Photographic recording material:** generally a plastic base coated with an emulsion

- **Emulsion** = layer of gelatin containing photosensitive silver halide

- The fine-grained negative (electron micrograph) contains a more detailed and higher contrast image than that seen on the fluorescent screen

NOTE: J. Turek will give more details about photography of electron images. See also lecture notes, pp.86-93.

End of Sec.I.B.6

I.B DESIGN OF THE TEM

I.B.7 TEM Vacuum Systems

KEY CONCEPTS

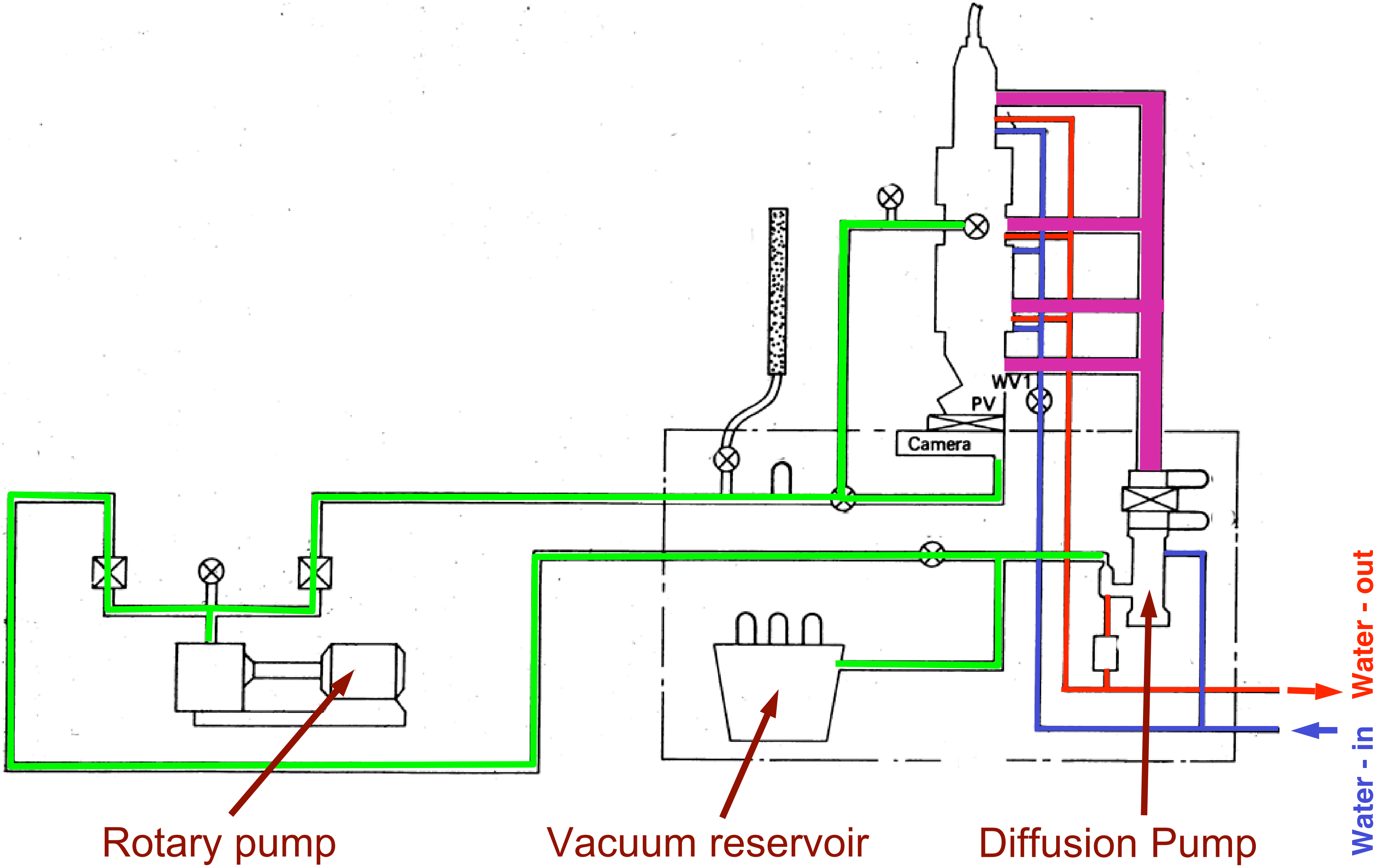
- High vacuum needed in order to allow passage of e^- through microscope

- **Mean free path** of an electron at atmospheric pressure (760 Torr) is a measly 6.5×10^{-6} cm (**65 nm!**)

- TEMs operate at **10^{-6} Torr** or lower (e- mean free path is > **50 meters!**)

- Most TEMs have at least two types of pumps in tandem

I.B.7 TEM Vacuum Systems



From Agar, Fig. 2.32, p.76

I.B.7 TEM Vacuum Systems

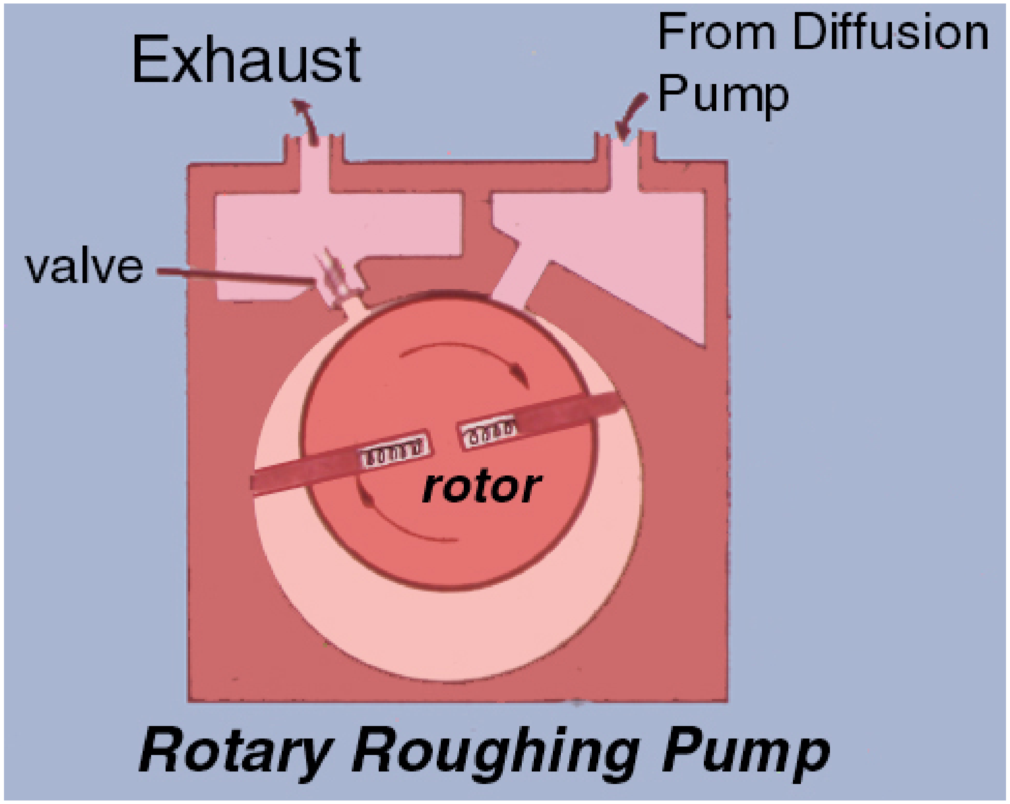
I.B.7.b Types of Pumps

Rotary Vane Pump

Mechanical pump that compresses and displaces trapped gases through the action of sliding vanes in a non-symmetrical chamber.

Pull a vacuum of 10^{-3} to 10^{-4} Torr

Often referred to as a **roughing pumps** since they do the initial “rough” pumping down from atmospheric pressure.



Rotary Roughing Pump

From Crang and Ward

I.B.7 TEM Vacuum Systems

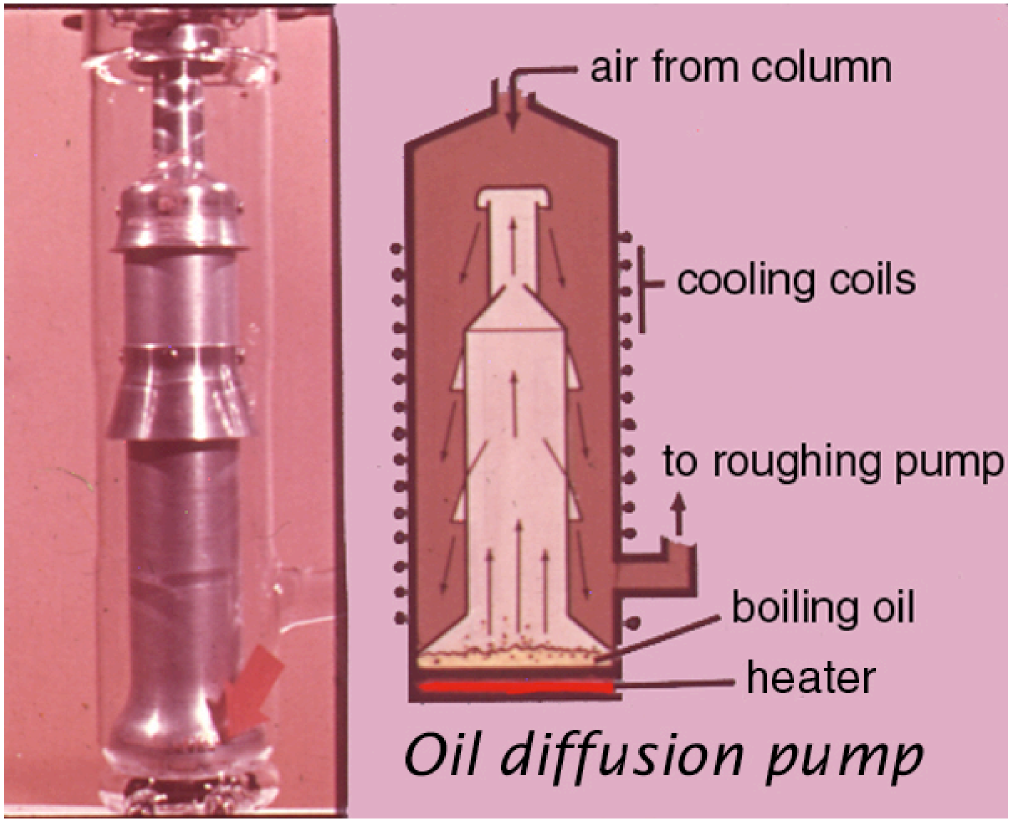
I.B.7.b Types of Pumps

Diffusion Pump

- Use hot oil vapor moving at supersonic speed to trap air molecules and remove them from the microscope.

- Diffusion pumps need to be backed up by rotary pumps since they require a backing pressure of at least 2 x 10^{-1} Torr to operate. They also require a water cooling source.

- Develop a vacuum of **10^{-5} to 10^{-7} Torr. High vacuum** is defined as 10^{-3} to 10^{-7} Torr. **Ultra-high vacuum** is below 10^{-7} Torr.



From Crang and Ward

I.B.7 TEM Vacuum Systems

I.B.7.b Types of Pumps

Ion Pump

- Vacuums as high as 10^{-9} Torr can be obtained by ionizing the particles to be out gassed in a strong electric field and subsequently causing them to be trapped at a surface.

- Many modern TEMs (*e.g.* FEI CM200 and CM300 FEG) use **ion getter pumps** to reduce the vacuum in the gun and specimen area to less than 10^{-7} Torr, thereby increasing filament lifetime and reducing specimen contamination

I.B.7 TEM Vacuum Systems

I.B.7.b Types of Pumps

Cryo Pump

If a **surface** is cooled below the condensation temperature of a vapor, it acts as an **effective pump**, since vapor reaching the surface cannot escape again.

Liquid nitrogen cooled surface is very effective for trapping organic vapors, but not lighter gases.

Other Pump Types

Turbomolecular Pump: An axial flow turbine pump consisting of alternating circular rotor and stator disks with inclined blades.

These pumps do not use oil vapor to establish high vacuum and **may be used alone**.

I.B.7 TEM Vacuum Systems

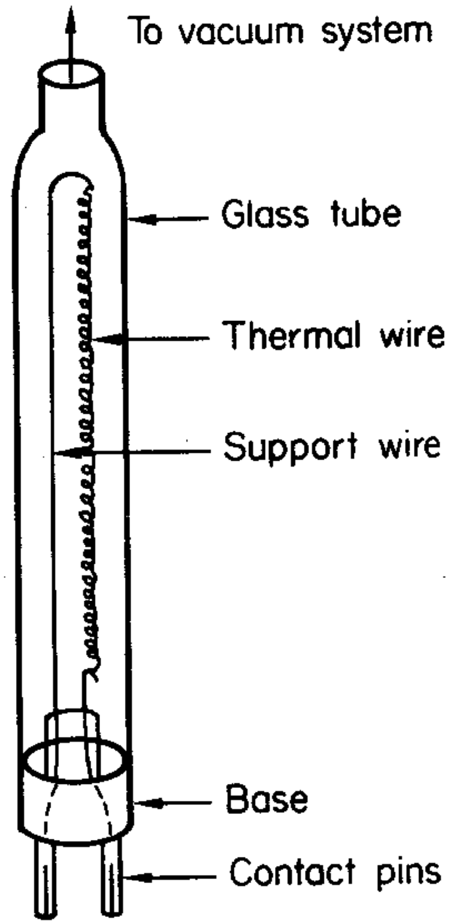
I.B.7.b Measuring Vacuum (Gauges)

Need to **monitor the quality** of the vacuum obtained by each type of pump

Pirani Gauge: Uses thermal conductivity to measure vacuum

- Heat dissipation from a heated filament is function of gas pressure

- Operate effectively from atmospheric pressure to ~10^{-4} Torr

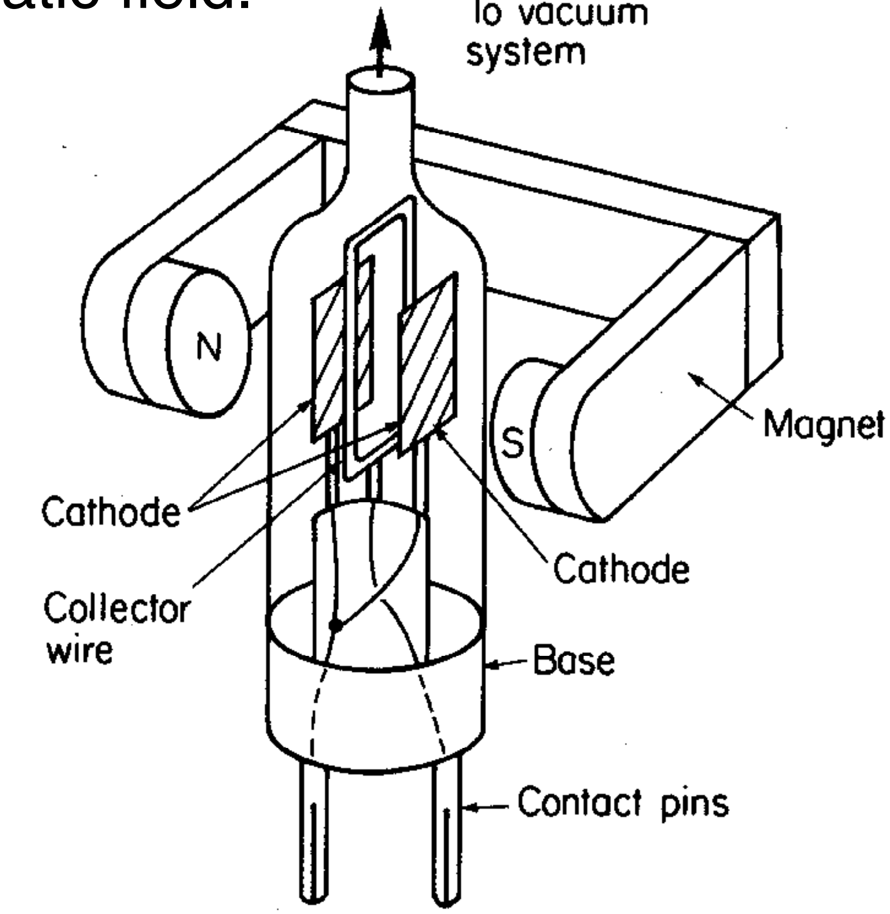


From Meek, 1st ed., Fig.6.3a, p.140

I.B.7 TEM Vacuum Systems

I.B.7.b Measuring Vacuum (Gauges)

Penning (Ion) Gauge: Depends on ionization of the gas molecules in a high electrostatic field.



- Electric field is developed between 2 cathodes and an anode which is placed between them.

- Effective from ~10^{-4} Torr and at higher vacuums

From Meek, 1st ed., Fig.6.4a, p.142

I.B.7 TEM Vacuum Systems

Limits to High Vacuum

- Pumping system will eventually come to an **equilibrium state** that is less than what is possible theoretically

- Air molecules stick to metal surfaces and are constantly being released

- Lint and dirt on O-rings leads to air leaks

- Photographic materials constantly leak water vapor, plasticizers, and other volatiles

- Grease on gaskets and O-rings are a source of hydrocarbon contamination

- Grease from **fingerprints** (*e.g.* on the specimen holder) contaminates everything in the vacuum

- **Cardinal Rule: Wear gloves** whenever handling any part exposed to the vacuum

I.B.7 TEM Vacuum Systems

Problems Caused by Poor Vacuum

Contamination of specimen: Hydrocarbon residue from oil, grease etc. gets hit by the e^- beam and decomposes to H and C. C atoms get fixed to the specimen and destroys resolution.

Decreased filament life due to etching of the filament

Beam can strip or etch the specimen. Residual water in the specimen is ionized and OH^- ions attack carbon in the specimen to make CO. This essentially ‘burns’ up the specimen.

Some of these problems are reduced or eliminated by use of an **anticontaminator**, which is a liquid N_2 cooled metal ring positioned near the specimen that traps contaminants before they reach the specimen.

End of Sec.I.B.7

I.B DESIGN OF THE TEM

I.B.8 Electrical System

I.B.8.a General Requirements

TEM electrical power supplies must provide:

- **Current to heat** the **filament** and generate image-forming electrons
- **High voltage** to accelerate the emitted e^- beam.
- **Current to each magnetic lens** to provide the necessary focusing magnetic fields.
- **Power to many circuits** such as stigmators, beam deflectors, camera, and camera shutter, exposure meter, focus wobbler, safety devices, relay switches, heaters of the diffusion pumps, the rotary pump, etc.

I.B.8 Electrical System

I.B.8.b Filament Current Supply

- Filament requires between **2.5-3 amps** as a heater current
- Supply is usually D.C. to avoid ripples that would modulate the e^- beam

I.B.8.c High Voltage Supply

- Must supply ~ 0.1 milliampere or less
- Accelerating potential supply is **high voltage and low current** (delivers 2-10 watts of power)

I.B.8 Electrical System

I.B.8.d Lens Current Supply

- Individual current supplies are required for each lens with **stabilities** of a **few parts per million**
- Supplies transistorized and operate at relatively low voltages. When high voltage to the gun is changed, a corresponding change is made in the lens currents to **maintain focus and magnification**
- Control of lens currents is programmed into the TEM so the correct lens combinations are obtained for minimizing distortion

I.B.8 Electrical System

I.B.8.e Stability Requirements

- For **high voltage stabilization**, stable high gain amplifiers with negative feedback from a resistive voltage divider between the cathode and ground are used

- High voltage generator is **enclosed in an oil-filled tank** (air not a good insulator)

- **Voltage** needs to be stable within **few parts per million**

I.B.8 Electrical System

I.B.8.e Stability Requirements

Lens Current Stabilization

- **Objective lens** has the **strictest stability requirement** of all the lenses (one part in 10^5)
- Stigmators and beam deflectors require stabilities of same magnitude as lenses and are generally fed from the lens circuits
- If current through any imaging lens varies, the image rotates about a point called the **current rotation center** (coincident with the viewing screen center if the microscope is properly aligned)

  Micrograph taken under these circumstances will be blurred at the edges and sharp at the center
- Fluctuating accelerating voltage gives rise to changes in magnification

  Image grows or contracts radially about a point called the **voltage center** which should be coincident with the center of the viewing screen

I.B.8 Electrical System

I.B.8.e Stability Requirements

Lens Current Stabilization

Recall: focal length of a magnetic lens is a function of the square of the current passing through the lens

$$f = \frac{KV_r}{(N \cdot I)^2}$$

- Hence, **current stability requirement** for an electromagnetic lens is higher than that of the accelerating voltage (by about a factor of 2)

- If, for example, accelerating voltage must be stable to one part in 5×10^4, then the lens current must be stabilized to within one part in 10^5 over the period required for recording the image (1-5 seconds)

End of Sec.I.B.8